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14. ABSTRACT

PATH IV is the latest product in the evolution of the Navy's PATH (Probability of Aircraft Tactical Hazards) series of safe escape models. PATH IV introduces a fully 3-dimensional model to describe the interaction between the aircraft and the warhead fragment cloud and uses fourth-order Runge-Kutta numerical integration to compute the trajectories of these fragments. Using a fully 3-dimensional model contributes to an increased accuracy in the description of the fragment cloud via 3-dimensional fragment cells. The model also simulates the physical situation in a more natural, intuitive manner than a 2-dimensional model can provide.

To minimize execution time on older, slower computers, the previous versions of the Navy's safe escape models principally used ballistic functions to compute the fragment trajectory data and thus approximated the actual position data for fragments. As weapon release altitudes have increased with increasing aircraft capability, the accuracy of these ballistic functions has degraded and has become unacceptable for high-altitude releases. Since current computers allow more flexibility in execution time, the use of numerical integration is now possible and removes this accuracy problem and at the same time allows the Navy to add capabilities that were not possible with the older ballistic functions.

The three previous versions of the Navy safe escape models were all coded in the FORTRAN programming language that minimized the range of problems for which these models could be used. The object-oriented design of PATH IV has allowed a more generalized design and increased its range of use. By providing the more general concepts of an 'object at risk' and a 'detonating object,' PATH IV allows for a broader range of possible scenarios and the inclusion of collateral damage and force protection computations. Safe escape studies involving more than one aircraft are also supported in PATH IV. The object-oriented design also greatly facilitates the extension of the model for future uses, particularly the inclusion of functionality for probability of damage or kill studies.

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Probability of Aircraft Tactical Hazards IV (PATH IV) Next Generation of Navy Model for Safe Escape

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Abstract

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Contents

1.0 Introduction

This paper discusses the mathematical model for PATH IV, the latest evolution in Navy safe escape models. After briefly stating the outputs for PATH IV, an explanation of how the model represents the aircraft and weapon is presented, including a description of the 2- and 3-dimensional static representation of the weapon detonation. Having described the inputs required for PATH IV, a description of the various analyses performed to minimize the number of fragment trajectories that need to be computed using numerical integration is presented. Once the total possible fragment trajectories have been reduced into the subset that presents a potential hazard to the aircraft, the methodology used to compute the probability that an aircraft is hit by fragments resulting from the detonation of a weapon is discussed. The paper concludes with a discussion of some of the new features and potential capabilities that are available in the PATH IV model.

2.0 Outputs of PATH IV

2.1 Probability of Hit

The probability of hit is the basic product of PATH IV. This value is the probability that an aircraft is hit by one or more fragments resulting from the detonation of delivered ordnance.

2.2 Minimum Altitude

PATH IV determines the lowest release altitude that keeps the probability of hit below a client-specified threshold value.

2.3 Maximum Stick Length

PATH IV determines the maximum stick length that keeps the probability of hit below a client-specified threshold value. In this context, stick length is measured in seconds and indicates the amount of time after first release that the pilot has to release his weapons.

2.4 Minimum Safe Separation

PATH IV determines the shortest slant range between release and detonation that keeps the probability of hit below a client-specified threshold value. This is used for safe escape studies involving air-to-air weapons.

3.0 Aircraft Representation in PATH IV

There are two main elements required to model the aircraft in PATH IV. The first is the time, space, position information (referred to as TSPI data) representing its trajectory. This data contains the times in the trajectory, as well as the position, velocity and Euler angles for the centroid of the aircraft at each time.

The other required element is a 3-dimensional representation of the spatial extent of the aircraft. An object referred to as a 'bounding volume' provides this representation in PATH IV. In the simplest case, this bounding volume could just be a rectangular parallelepiped. However, PATH IV is not limited to this representation. In general, the bounding volume representation consists of a collection of rectangular solids and tetrahedra. The rectangular solids need not consist entirely of right angles, but they are assumed to be convex.

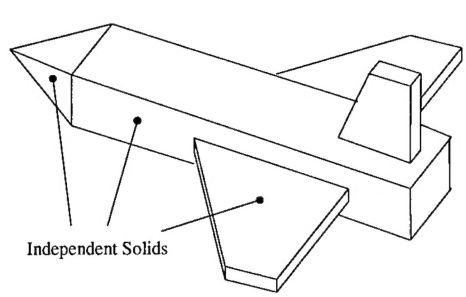

Figure 1: Example of an Aircraft Bounding Volume

4.0 Weapon Representation in PATH IV

PATH IV also requires TSPI data representing the weapon trajectory. These data contain the times in the trajectory, as well as the position, velocity and Euler angles of the weapon at each time. The Euler angles of the weapon at burst are important so that the static fragment vectors can be correctly oriented prior to numerically integrating to obtain the fragment trajectories. Actually, an entire weapon trajectory is not required, but only the TSPI data for the weapon at the time of burst.

As PATH IV will be modeling the detonation of a weapon, it also requires some characterization of the weapon detonation. These characteristics are physically obtained through the detonation of weapons in a test arena. The results of these arena tests are input to PATH IV via static fragmentation files.

5.0 Static Fragmentation Files

Associated with each weapon is a static frag file that contains information about the detonation characteristics of the weapon. These files provide a 2-dimensional representation only. As each and every fragment of the weapon cannot be modeled in a timely manner, a representative set of fragments must be used that has been defined for each weapon through arena testing. The following sections describe the data elements contained within the static frag files.

5.1 Polar Angles

The polar angles are the angles relative to the longitudinal axis of the weapon from which the fragments exit the weapon upon detonation (see Figure 2). The region between two consecutive polar angles is defined as a *polar zone.*

5.3 Reciprocal Ballistic Coefficients (Gammas)

These values define the drag characteristics for the representative set of fragments and are referred to as *gammas.* The gammas take into consideration the weight of a fragment as well as the fragment shape (i.e. presented area). These values are determined by collection and analysis of the actual fragments after detonation in an arena test. For reference, let $\Gamma = \{\gamma_0, \gamma_1, \ldots, \gamma_n\}$, where the indices go in order of *decreasing* weight, i.e. γ_0 is the heaviest fragment, γ_n the lightest. The 'region' between two consecutive gamma values is defined as a *gamma zone.*

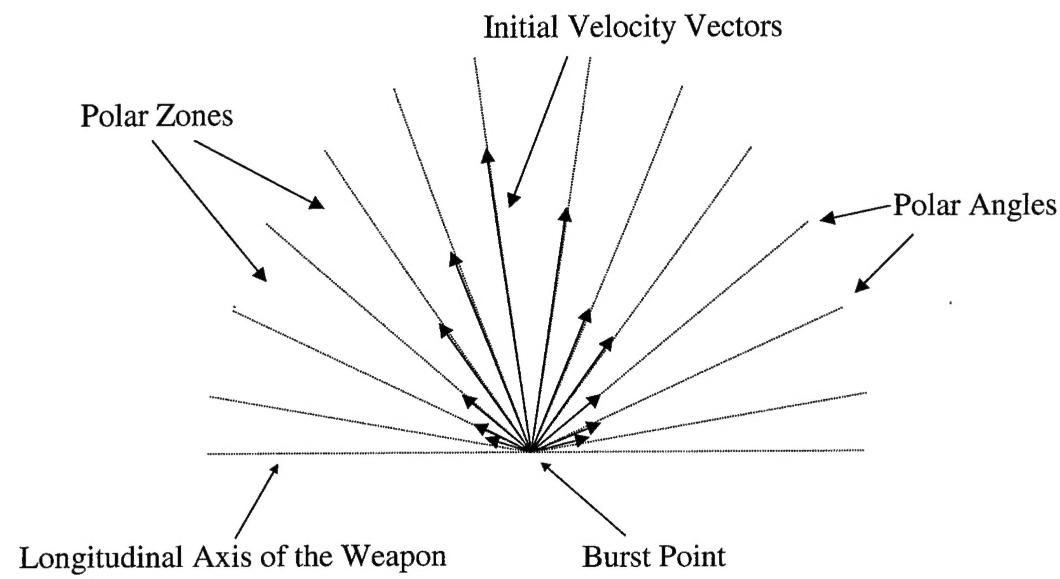

Figure 2: Elements of the Static Frag Data

5.2 Initial Velocities

An initial velocity is associated with each polar angle and gives us the speed at which a fragment exits the weapon for that particular polar angle. Every fragment that is launched from a particular polar angle is assumed to have the same initial velocity. For reference, let $V = \{v_0, v_1, \ldots, n_n\}$, where v_i is the velocity at the i^{th} polar angle, and define $v_{\max} = \max(V)$, i.e. $v_{\max}$ is the highest exit velocity of all the polar angles.

5.4 Number of Fragments

This is the number of fragments in a 2-dimensional *polar/gamma zone.* In

the 2-d representation, a polar/gamma zone is the region defined by two consecutive gammas being launched from two consecutive polar angles (see Figure 3).

- Rotates each of these vectors through 360 degrees, in 15 degree increments. At every increment a new vector is created. These increments are the *roll angles*, and the region between two consecutive roll angles is defined as a *roll zone*.

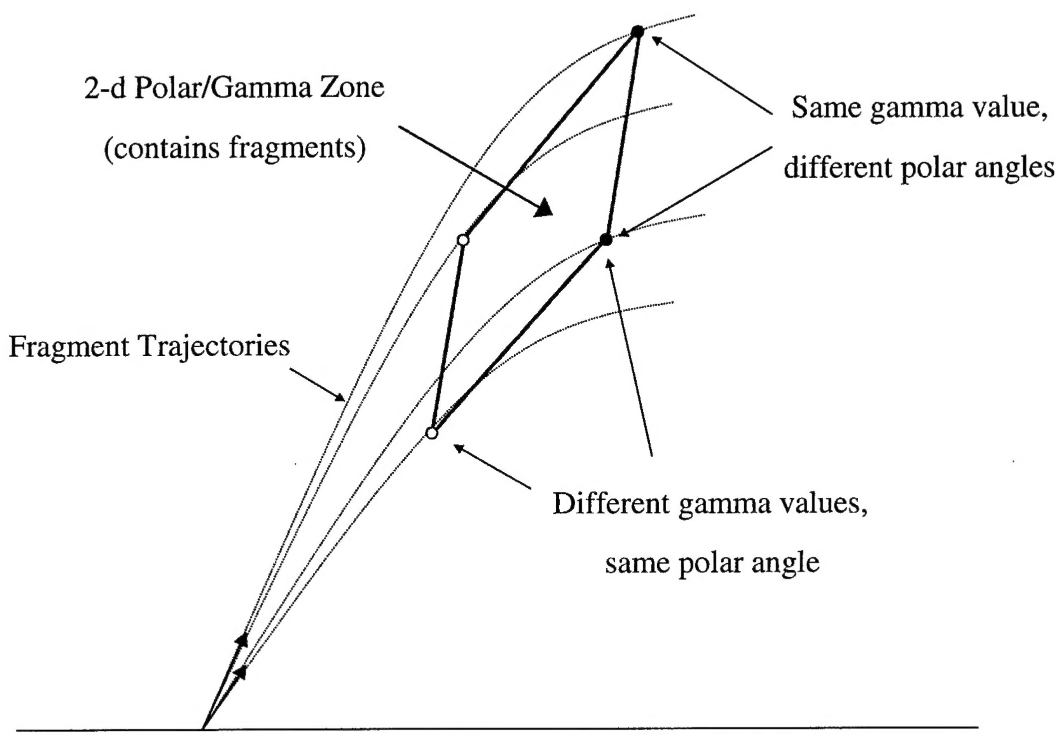

Figure 3: Two-Dimensional Depiction of a Polar/Gamma Zone

6.0 3-Dimensional Representation of the Static Weapon

To create a static, 3-dimensional view of the weapon, PATH IV performs the following operations:

- Constructs a unit vector directed along each polar angle.*

- Multiplies each unit vector by the initial velocity associated with the polar angle.

* Actually, the vectors are only created for the polar angles between 0 and 180 degrees as the data in the static fragmentation files are symmetric about the longitudinal axis of the weapon.

The vectors constructed above are referred to as *static frag vectors*.

Before PATH IV uses these static frag vectors for analysis or as initial conditions for launching fragments, the

velocity and orientation of the weapon at the time of burst must be accounted for. To account for these, PATH IV performs the following operations:

- Using the weapon TSPI data, the velocity components of the weapon at burst are obtained and a vector representing this velocity is constructed.
- Using the weapon TSPI Data, the Euler angles of the weapon at burst are obtained. These angles give us the orientation of the weapon at burst.
- The burst velocity vector is added to each of the static frag vectors.
- Each of the velocity adjusted static frag vectors is rotated through the Euler angles of the weapon.

At this point PATH IV has defined a static picture of the weapon at the time of burst. These static vectors can now be utilized to initialize out trajectory integrator and create TSPI data for each of the gammas of the detonated weapon.

7.0 Max Frag Envelope Computations

Before initiating a detailed analysis of the frag zones and performing all of the computations required to generate the fragment trajectories, PATH IV performs a Max Frag Envelope (MFE) computation. The purpose of this computation is to quickly determine if it is even possible for the aircraft to be hit by any fragments from the weapon. This is accomplished by computing the trajectory for the theoretical 'max frag.' To compute this max frag trajectory, PATH IV uses the heaviest fragment (i.e. γ_0) that exists in the static frag file and the highest exit velocity of all the polar angles (i.e. v_{max}). This fragment is aimed directly at the aircraft and fired off. Using the heaviest weight and the highest exit velocity in essence determines the maximum envelope possible for any fragment that exits from the weapon. That is to say, if the aircraft does not enter this max frag envelope, PATH IV concludes that it cannot be hit by any of the fragments from the weapon. Algorithmically:

- Using the aircraft TSPI data, PATH IV obtains the position of the aircraft at the time of weapon burst.
- A unit vector is constructed which is directed from the weapon burst point to the aircraft position at the time of burst.
- The unit vector is multiplied by v_{max} obtained from the static frag file for the weapon.
- The trajectory integrator is initialized with γ_0 and the initial velocity vector.
- The fragment trajectory is computed and its TSPI data is retrieved.

Once PATH IV has obtained the TSPI data for the max frag, it can determine if the aircraft enters the MFE in the following manner:

- Using the aircraft TSPI data, PATH IV obtains the position of the aircraft at each time step, t_i,

and computes the aircraft slant range, $s_{ac}(t_i)$, from the burst point.

- From the max frag TSPI data, PATH IV obtains the position of the frag at the same time step, t_i, and computes the frag slant range, $s_{frag}(t_i)$, from the burst point.

- Having determined that the aircraft enters the MFE, PATH IV continues to compute slant range differences until $s_{diff}(t_j) = s_{ac}(t_j) - s_{frag}(t_j) > 0$. The first time step t_j for which $s_{diff}(t_j) > 0$ is the time that the

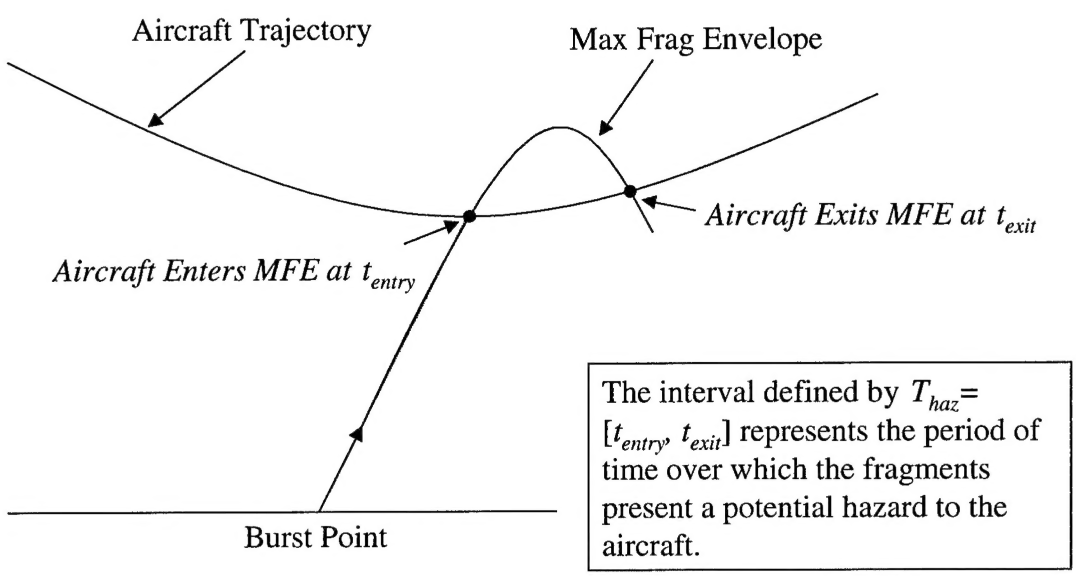

Figure 4: Two-Dimensional Depiction of Max Frag Envelope (MFE) Interaction

aircraft exits the max frag envelope and is defined as t_{exit}. This is considered to be the last point in time after weapon burst that the aircraft is exposed to a potential fragment hazard. The total time interval over which the aircraft is exposed is defined as $T_{haz} = [t_{entry}, t_{exit}]$.

- If $s_{diff}(t_i) = s_{ac}(t_i) - s_{frag}(t_i) \leq 0$, it is concluded that the aircraft has entered the MFE and therefore a more detailed analysis of the frag zones is required. The first time step t_i for which $s_{diff}(t_i) \leq 0$ is the time that the aircraft enters the max frag envelope and is defined as t_{entry}. This is considered to be the first point in time after weapon burst that the aircraft is exposed to a potential fragment hazard.

- If for two consecutive times steps, $t_i < t_{i+1}$, it is found that $s_{diff}(t_i) < s_{diff}(t_{i+1})$, i.e. the distance

between the aircraft and the max frag is beginning to increase, PATH IV stops the slant range computations and concludes that the aircraft is beginning to 'outrun' the max frag and therefore does not enter the MFE. As a result, the probability of hit is zero and the simulation is complete at the expense of having computed only a single fragment trajectory.

8.0 Defining Intersection Zones

Computing fragment trajectories for every gamma and at every polar/roll angle combination would be computationally expensive and logically unnecessary. In most cases PATH IV only has to be concerned with a small subset of the polar/roll angles, as many fragments will not be directed towards the aircraft for any point in their trajectory. A particular example of this is when the aircraft is always above the burst plane. In this case, the only fragments presenting a potential hazard are those whose static frag vectors are directed above the burst plane, while the rest may be ignored. This alone reduces the total number of frag trajectories by half. In addition, the aircraft may not penetrate very deeply into the frag cloud. In this case, trajectories of some of the lighter fragments may not be necessary. PATH IV performs several analyses in an effort to minimize the number of fragment trajectories that need to be computed.

9.0 Identification of Hazardous Gamma Zones

Initially PATH IV determines which gamma zones provide a potential threat to the aircraft. The gamma zone into which the aircraft enters is in effect a measure of how deeply it penetrates into the frag cloud. To make this determination, PATH IV reuses the concept of the max frag envelope. In this case however, instead of finding the

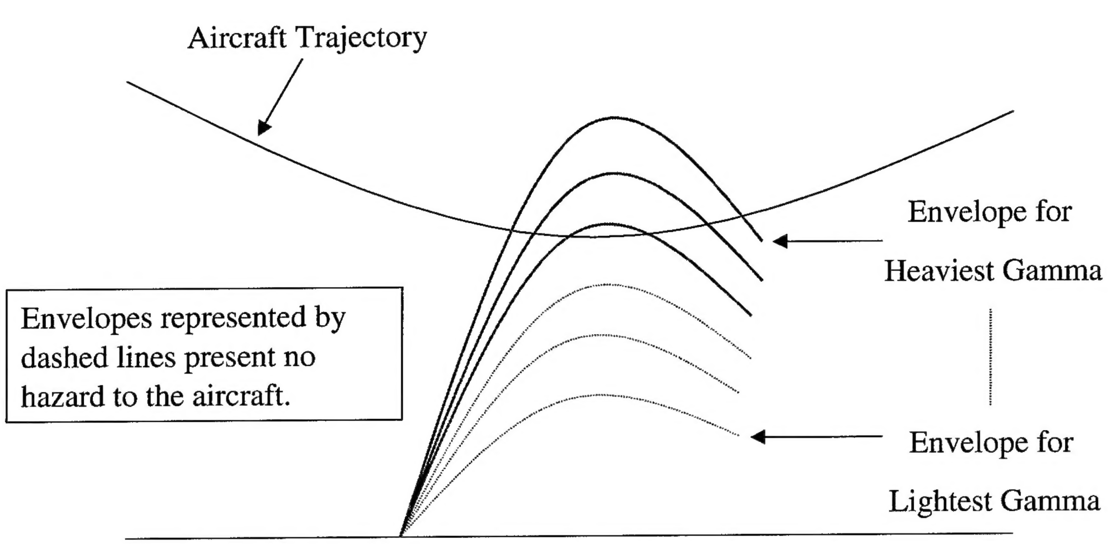

Figure 5: Identifying Hazardous Gamma Zones

MFE for the weapon as a whole, the MFE for each individual gamma zone is determined independently.

PATH IV begins by computing the MFE for γ_1 and performing the same sequence of calculations with the slant ranges to determine the time at which the aircraft enters the MFE (see Section 7.0 - Max Frag Envelope Computations). If the aircraft enters the MFE for γ_1, the model then proceeds to γ_2, computes its MFE and determines if the aircraft enters into it.

Once PATH IV has found the γ_i whose MFE is not entered by the aircraft, the deepest gamma zone into which the aircraft penetrates has been determined. The remaining γ_j, for $j > i$ can be ignored, as these fragments are lighter than γ_i, and consequently they will all have a lower MFE's (see Figure 5).

10.0 Identification of Hazardous Polar/Roll Zones

Having minimized the gammas that need to be considered, PATH IV then proceeds to identify the static polar/roll zones that present a potential hazard to the aircraft. The polar/roll zones are only analyzed for times within T_{haz}. For every static *polar/roll zone* (i.e. a zone define by 2 consecutive roll angles and 2 consecutive polar angles), PATH IV performs the following operations:

- The four static frag vectors that define the polar/roll zone are projected into the burst plane.
- The two static frag vectors whose projections into the burst plane have the greatest angle between them are retained.

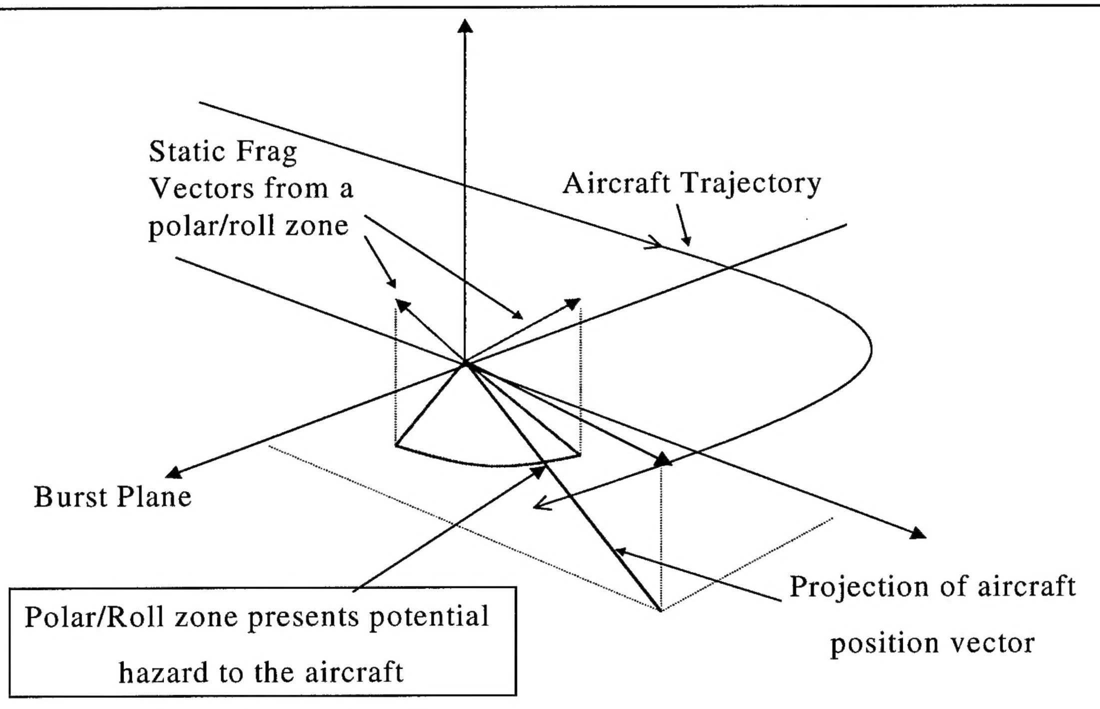

Figure 6: Identifying a Hazardous Polar/Roll Zone

- For each time step $t_i \in T_{haz}$:
  - The position vector of the aircraft from the burst point is determined.
  - The aircraft position vector is projected into the burst plane.

- If the projection of the aircraft position vector falls between the projections of the two static frag vectors, PATH IV concludes that the polar/roll zone presents a potential hazard to the aircraft (see Figure 6).

- If the projection of the aircraft position vector does not fall between the projections of the two static frag vectors for all $t_i \in T_{haz}$, PATH IV concludes that the polar/roll zone does not pose a hazard to the aircraft.

Having independently analyzed the gamma zones and the polar/roll zones, PATH IV has determined the subset of static frag vectors that poses a potential hazard to the aircraft. PATH IV uses these vectors to initialize the trajectory integrator and compute TSPI data for the fragments

11.0 Dynamic Fragment Data

Having reduced the total number of static frag vectors to a minimal subset, PATH IV generates the TSPI data representing the actual fragment trajectories. TSPI data for each fragment are obtained from the integrator. This collection of TSPI data is referred to as the *dynamic fragment data* for the weapon. From these dynamic frag data, PATH IV constructs 'fragment cells' for every necessary combination of polar/roll/gamma zone.

12.0 Computing the Probability of Hit

12.1 Determining Intersections Between a Fragment Cell and the Aircraft

Initially PATH IV seeks to find the first time for which the aircraft bounding volume and a frag cell intersect. For each time step $t_i \in [t_{burst}, t_{exit}]$, the position of the aircraft bounding volume in space is compared with the position of the frag cell to see if they intersect. The first time step for which the intersection is non-zero is defined as the frag cell entry time, $t_{cellEntry}$. If t_{exit} is reached and no intersections were found, PATH IV concludes that there is no interaction between the aircraft and the frag cell being analyzed. Consequently, no probability of hit is accumulated from this frag cell.

If an intersection is found, PATH IV continues to compare the aircraft bounding volume and frag cell at each time step until they no longer intersect. The time at which the intersection becomes zero is defined at the frag cell exit time, $t_{cellExit}$. It has been shown that the aircraft can exit a frag cell and reenter it at a later time. PATH IV does account for these multiple entries into the same frag cell.

12.2 Computing the Probability of Hit for the Aircraft-Frag Cell Interaction

At this point PATH IV has determined that there exists a time interval, $T_\cap = [t_{cellEntry}, t_{cellExit}]$, in which the aircraft bounding volume and frag

cell intersect. During this time interval a non-zero probability that the aircraft is hit by one or more fragments within the frag cell will be accumulated. $T_{\cap}$ is broken down into equal time intervals, Δt. For each of these values of Δt, PATH IV performs the following operations:

- The average aircraft velocity vector, $\bar{v}_{ac}$, is computed.

- The average frag cell velocity vector, $\bar{v}_{fc}$, is computed.

- Using these vectors, the average relative velocity vector between the aircraft and frag cell, $\bar{v}_{rel} = \bar{v}_{ac} - \bar{v}_{fc}$, is computed.

- The area that the aircraft 'presents' to the frag cell, A_{pres}, is computed. This is the area of the projection of the aircraft into the plane perpendicular to the relative velocity vector, $\bar{v}_{rel}$.

- The volume swept out by the aircraft, V_{ac}, is computed. This is determined by taking the presented area determined previously and multiplying it by the magnitude of the relative velocity vector and the time step:

$$V_{ac} = A_{pres} \cdot |\bar{v}_{rel}| \cdot \Delta t$$

- The volume swept out by the frag cell, V_{fc}, is computed.

- Once the volumes swept out by the aircraft and the frag cell over Δt have been determined, PATH IV computes the probability of hit that occurs over this time step, $P_{\Delta t}$. Depending on whether the client has specified the fragment distribution as Poisson or uniform, the probability over the time step is found by:

$$P_{\Delta t} = 1 - \exp\left(-n\frac{V_{ac}}{V_{fc}}\right)$$

(Poisson)

$$P_{\Delta t} = 1 - \left(1 - \frac{V_{ac}}{V_{fc}}\right)^n$$

(Uniform)

where n is the number of fragments in the frag cell under analysis.

- PATH IV computes a probability of hit for each Δt in the intersection time interval, $T_{\cap}$. Once these have been computed, they are summed in a probabilistic manner:

$$P_{cell} = 1 - \prod_i \left(1 - P_{\Delta t_i}\right)$$

where i ranges over the number of time intervals in $T_{\cap}$. The value P_{cell} is the probability that the aircraft is hit by fragments from the frag cell under analysis.

- This same procedure is performed for each frag cell in the dynamic frag data. Once a probability of hit has been obtained for each frag cell, they are summed in the same fashion as was done for the time intervals:

$$P_{hit} = 1 - \prod_{j} \left(1 - P_{cell\,j}\right)$$

where j ranges over the total number of frag cells that presented a hazard to the aircraft. The value P_{hit} is the total probability of hit for the aircraft for this particular delivery.

12.3 Probability of Hit for Multiple Weapons

If multiple weapons are released, the procedure given in Section 12.2 is carried out for each individual weapon. A probability of hit is determined for each weapon and then summed probabilistically to compute the cumulative probability of hit.

12.4 Variation in the Striking Angle

It has been shown that a relatively slight change in orientation of the weapon at the time of burst can have a substantial impact upon the resulting probability of hit. The variable that plays the most significant role is the striking angle. This is the angle that the longitudinal axis of the weapon makes with the horizontal at the time of burst. Because the striking angle is measured with respect to the longitudinal axis, varying it changes (potentially) the polar zones that present a hazard to the aircraft (see Figure 7). This can be significant as adjacent polar zones may contain substantially different numbers of fragments, directly impacting the probability of hit.

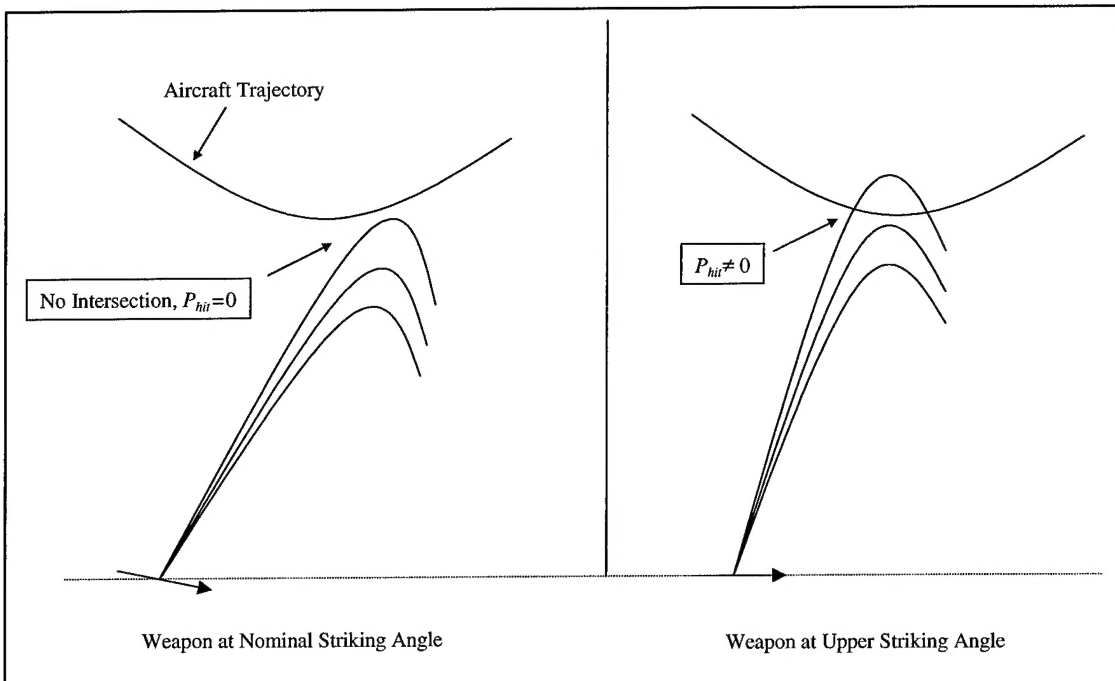

Figure 7: Variation in Striking Angle Influencing P_{hit}

When PATH IV computes the probability of hit between an aircraft and a weapon, internally it will vary the striking angle of the weapon by ± 10 degrees about the nominal (the nominal being the actual orientation of the weapon given by its TSPI data). It will compute the probability of hit for the nominal orientation, the orientation at $+10$ degrees (referred to as the upper striking angle) and the orientation at -10 degrees (referred to as the lower striking angle). The value that is returned to the client as the actual probability of hit for the scenario is the largest of these three probabilities.

This variation in the striking angle is designed to accommodate for a number of approximations that can propagate through the model. For example, inherent uncertainty in the static frag data, approximations made in weapon or aircraft models, uncertainty in exact positions and orientations in these models, etc. It also allows for the possibility that in reality the aircraft may not be following the exact trajectory determined by a computer model, i.e. the pilot's true position in space may be different from this theoretical ideal. This being said, a client of PATH IV may still elect not to utilize the striking angle variations by explicitly setting the variation to zero, or may specify a variation other than the ten-degree default.

13.0 New Features and Capabilities of the PATH IV Safe Escape Model

The methodology and design provided by PATH IV allows for a greater flexibility in safe escape modeling and also expands the scenarios which can be modeled.

13.1 Collateral Damage and Other General Studies

While a safe escape model is usually thought of as simulating a load of ordnance being delivered by an aircraft, the PATH IV design is not limited to this particular scenario. The idea can be generalized by thinking of the aircraft as an instance of the more general concept of 'object at risk.' Similarly the bomb can be generalized by thinking of it as an instance of the more general concept of 'detonating object.' It should be noted that what essentially defines the model is:

- TSPI data for the object at risk
- A representation of the spatial extent of the object at risk
- TSPI data for the detonating object
- Fragmentation characteristics for the detonating object.

Using this reasoning, a rudimentary model of a scenario such as collateral damage can be provided. In this case, the object at risk could be a building which is not to be exposed to some level of damage. The building could be represented by a bounding volume which is just a tall rectangular solid. As the building is stationary, its TSPI data would simply be constant over time. In this case, the detonating object might still be a bomb. As long as the burst conditions are specified and fragmentation characteristics (e.g. static fragmentation data) are provided, PATH IV could compute a probability of fragment hit to the building. While this is just a rough sketch, hopefully it

helps illustrate the flexibility and extendibility of the PATH IV model to scenarios other than the traditional aircraft-bomb combination.

13.2 Fragment Distribution

PATH IV allows the fragments to be distributed within their cells in either a uniform or Poisson distribution. The client selects which method they wish to utilize.

13.3 Freedom of Choice in Aircraft and Weapon Models

The design of PATH IV allows the client to use any aircraft and weapon model he desires. All that PATH IV requires is that the TSPI data presented to it follow a particular format. The source of that TSPI data is purely at the discretion of the client.

13.4 Multiple Weapon and Mixed Store Delivery

PATH IV will model the delivery of multiple weapons from an aircraft. These can be GP bombs, guided weapons, rockets, missiles, etc. PATH IV computes a probability of hit for each weapon independently, as well as the overall (i.e. cumulative) probability of hit for the entire load. As each weapon has its own static frag data, PATH IV also models the delivery of mixed loads, if necessary.

13.5 Probability of Hit to Follow-On Aircraft

PATH IV can determine the probability that a follow on aircraft is hit by fragments from ordnance delivered by an earlier aircraft. The client provides the aircraft TSPI data for the follow on aircraft, but provides weapon TSPI data for the weapons delivered by the preceding aircraft.

13.6 Probability of Kill Studies (Major Damage)

PATH IV does not currently perform major damage or kill studies. However, it was designed with the future implementation of these studies in mind. Consequently, a good portion of the basic functionality used in performing the hit studies will be reusable once major damage or kill studies are better defined.

14.0 Addendum: Brief Description of Arena Test

The fragmentation characteristics of a weapon (i.e. the fragment weights, spatial distributions and velocities), are obtained from static detonations of one or more weapons in a circular arena, which is known as an arena test. In a typical arena, approximately one-half of the circular wall is composed of Celotex panels marked off by the traces of polar angles. At detonation, a fraction of the fragments projected from the weapon are embedded in the Celotex wall. These fragments are recovered, weighed and classified by polar zone/weight groups.

Correspondingly, velocity data for fragments within each zone are obtained by photographing penetrations of the mild steel plates that form the remaining one-half of the arena. All penetrations are recorded in each zone. Each recording provides a time of travel over

the radius of the arena, thus permitting a determination of the average velocity. Because each measured velocity cannot be correlated with the fragment that produces it, an initial velocity for each zone is computed based on the mean of the measured velocities and the mean weight of the recovered fragments in the zone.